Design and Development of the CubeSat Infrared Atmospheric Sounder (CIRAS)

Thomas S. Pagano*, Carlo Abesamis, Andres Andrade, Sarath Gunapala, Cate Heneghan, Robert Jarnot, Dean Johnson, Andy Lamborn, Yuki Maruyama, Sir Rafol, Nasrat Raouf, David Rider, Dave Ting, Dan Wilson, Karl Yee
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr., Pasadena, CA 91109

Jerold Cole, Bill Good, Tom Kampe, Juancarlos Soto
Ball Aerospace and Technologies Corporation
Boulder Co, 80301

Arn Adams, Matt Buckley, Richard Graham, Fred Nicol, Tony Vengel,
IRCameras
Santa Barbara, Ca 93103

ABSTRACT

The CubeSat Infrared Atmospheric Sounder (CIRAS) is a NASA Earth Science Technology Office (ESTO) sponsored mission to demonstrate key technologies used in very high spectral resolution infrared remote sensing of Earth's atmosphere from space. CIRAS was awarded under the ESTO In-flight Validation of Earth Science Technologies (InVEST) program in 2015 and is currently under development at NASA JPL with key subsystems being developed by industry. CIRAS incorporates key new instrument technologies including a 2D array of High Operating Temperature Barrier Infrared Detector (HOT-BIRD) material, selected for its high uniformity, low cost, low noise and higher operating temperatures than traditional materials. The second key technology is an MWIR Grating Spectrometer (MGS) designed to provide imaging spectroscopy for atmospheric sounding in a CubeSat volume. The MGS is under development by Ball Aerospace with the grating and slit developed by JPL. The third key technology is an infrared blackbody fabricated with JPL's black silicon to have very high emissivity in a flat plate construction. JPL will also develop the mechanical, electronic and thermal subsystems for CIRAS, while the spacecraft will be a 6U CubeSat developed by Blue Canyon Technologies. This paper provides an overview of the design and acquisition approach, and provides a status of the current development.

Keywords: Infrared, Sounding, CubeSat, Grating, Spectrometer

1. INTRODUCTION

Hyperspectral radiances measured from Low Earth Orbiting (LEO) infrared (IR) sounders including the NASA Atmospheric Infrared Sounder (AIRS)[1] on Aqua, and the Cross-track Infrared Sounder (CrIS) on the Joint Polar Satellite System (JPSS) have among the highest impact of any measurement type when assimilated into operational weather forecast models[2,3,4]. LEO IR sounder radiances are used to retrieve temperature and moisture profiles with high vertical accuracy.[5] AIRS profiles have been used to validate water vapor distributions in climate models and confirm positive water vapor feedback to global warming.[6,7] CIRAS is a technology demonstration to achieve IR sounding in a 6U CubeSat[8].

Figure 1 shows a conceptual layout of the CIRAS instrument. Success criteria for CIRAS are

- Successful operation of key technologies (MGS, HOTBIRD and Black Si) in a Spaceborne Environment
- Successful on-obit demonstration of an infrared sounder spectrometer in a 6U CubeSat form factor
- Successful acquisition of at least 100 hours of data over a 3 month period

*thomas.s.pagano@jpl.nasa.gov, phone: (818) 205-4702, http://airs.jpl.nasa.gov
The potential significance of CIRAS to support weather prediction supported its selection by the NASA Earth Science Technology Office (ESTO) under the Inflight Validation of Earth Science Technology (InVEST) program. The CIRAS is currently under development at NASA JPL and is scheduled for launch in 2019. The payload uses a mix of commercial and custom hardware with industry partners including Ball Aerospace, IRCameras and Blue Canyon Technologies (BCT). The key new technologies (immersion grating, focal plane, black silicon blackbody) are developed at JPL's microdevices laboratory and have never flown before. Almost everything else, except parts of the payload electronics, is commercial or based on commercial designs. The CIRAS spacecraft will be based on the XB6 6U CubeSat developed by Blue Canyon Technologies. The CIRAS payload will be integrated at NASA JPL, while the complete system will be integrated and tested at BCT. CIRAS is currently scheduled to be complete in late 2018.

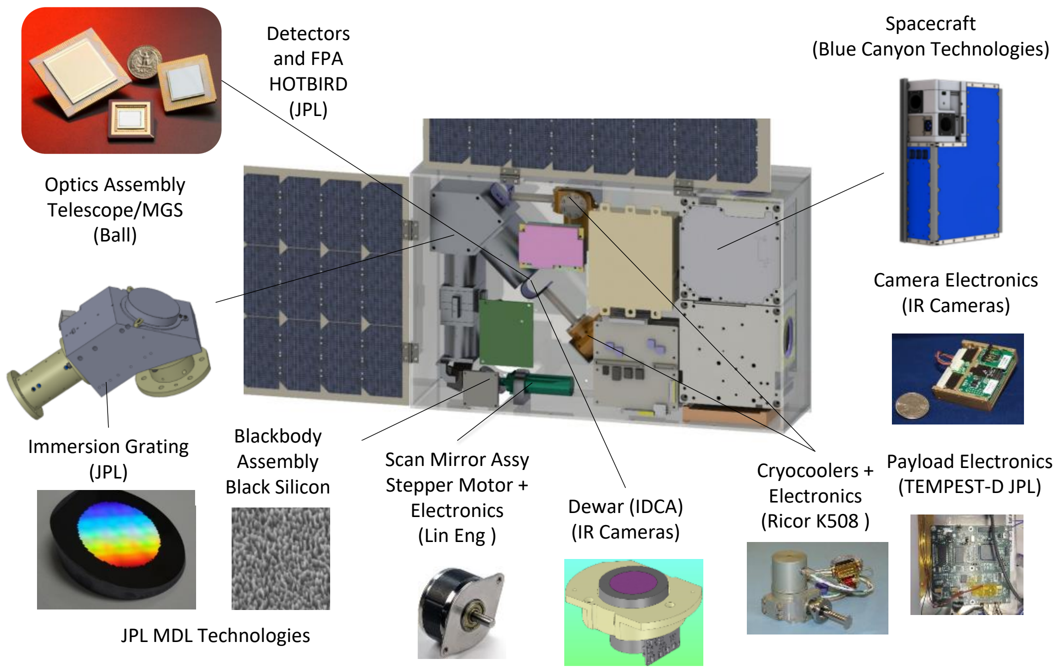

Figure 1. The CubeSat Infrared Atmospheric Sounder (CIRAS) and Major Subsystems.

2. CIRAS DESIGN OVERVIEW

A block diagram of the CIRAS is shown in Figure 2. The CIRAS payload includes a scan mirror capable of rotating 360º to view Earth, cold space and an internal blackbody for calibration. The scan mirror is driven by a high detent microstepper motor by Lin Engineering. Attached to the motor is an indexer that is used to determine the start position of each scan profile. The blackbody is a simple flat plate composed of black silicon, thermally isolated from the spacecraft and instrumented with a temperature sensor. Black silicon offers very high emissivity in a compact flat plate construction and is more robust than carbon nanotubes. The system is calibrated by viewing space and the on-board blackbody with the scan mirror before and after each Earth view.

Energy from the scan mirror is collected using an all-refractive telescope. Energy from the telescope is focused onto the entrance slit of an all refractive MWIR Grating Spectrometer (MGS). The MGS covers the 4.08-5.13 µm spectral range in 625 channels and employs an immersion grating to reduce size and distortion. This band was selected because it contains a CO_2 absorption feature near 4.1µm that can be used for temperature sounding and continues well into the water vapor continuum at longer wavelengths for water vapor sounding. The spectral response of the system resolves the absorption features with sufficient resolution to provide good vertical resolution of the profiles. The CIRAS optics will be developed by Ball Aerospace of Boulder Co. JPL will develop the immersion grating using e-beam etching technology and the entrance slit made of black silicon.

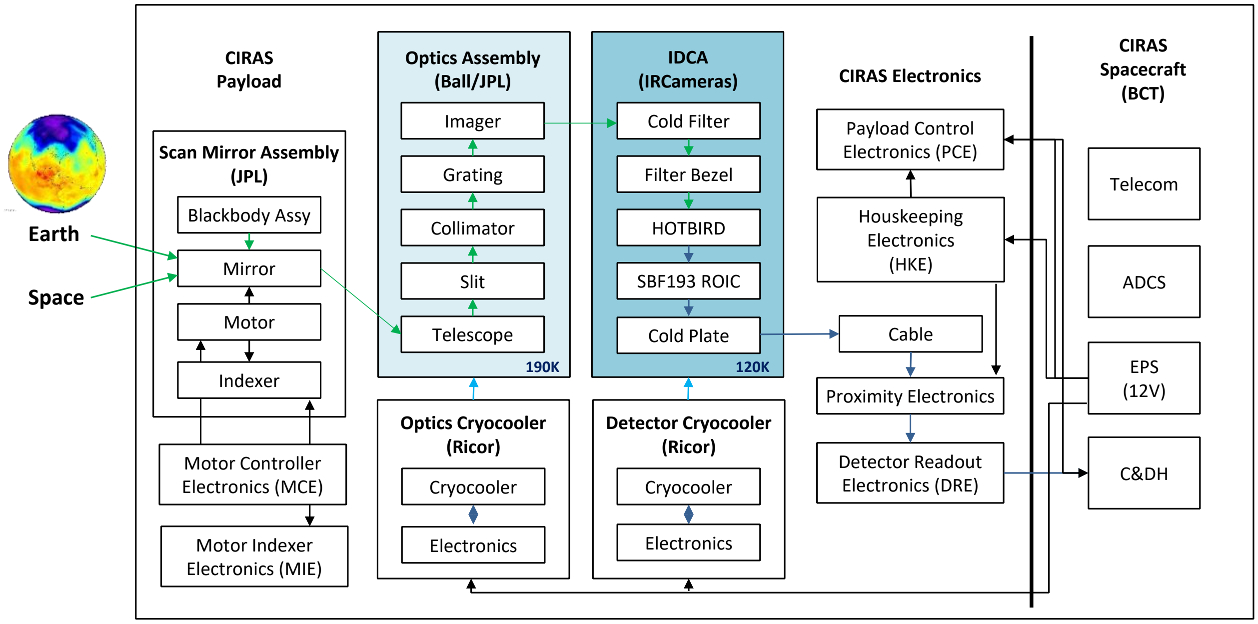

Figure 2. Block diagram of the CIRAS instrument.

The telescope and spectrometer are cooled to 190K using a Ricor K508N heat sunk to the chassis. The spectrometer disperses the energy across the spectral range and produces a 2-dimensional image at the focal plane with one direction spatial (504 pixels) and the other spectral (625 channels). The detector array uses the JPL HOT-BIRD photosensitive material mounted on a Lockheed Martin Santa Barbara Focalplane (SBF) 193 Readout Integrated Circuit (ROIC). The ROIC is mounted in a standard Integrated Cooler Dewar Assembly (ICDA) developed by IRCameras. The IDCA provides vacuum, cold shielding and spectral filtering of unwanted out-of-band and Ghosting energy. The detector is cooled to 115K using a second Ricor K508N cryocooler with cold tip contained within the IDCA and with the compressor heat sunk to the chassis. Cryocoolers run autonomously once turned on from power directly from the spacecraft bus.

Clocks, biases and A/D conversion are performed using commercial electronics contained in a combination of the Proximity Electronics and Detector Readout Electronics (DRE). Detector signals from the DRE go directly into the spacecraft through a “Camera Link” interface. Payload Control Electronics (PCE) control the Motor Control Electronics (MCE) that drives the scan motor, and the Motor Indexer Electronics (MIE) that control read the indexer. Housekeeping Electronics (HKE) read housekeeping data, temperature sensors and provide power to the DRE. Electronics, cryocooler and spacecraft waste heat is dissipated into the chassis.

The CIRAS spacecraft will operate in a sun synchronous orbit at an altitude ranging from 400-600 km and provide 12V power at 2A supporting payload activation and operations. Current estimates indicate the spacecraft can provide one full orbit of Earth pointing for data acquisition out of 3 orbits, with the other two orbits used for charging the batteries. The current plan is for the spacecraft to use the Cadet UHF radio. Data collection will be sized to match the data downlink capability. The spacecraft provides spatial and temporal binning of data from the FPA in the on-board computer to match the particular data acquisition mode. The pointing knowledge budget 1-sigma from all contributors of 0.3 pixels (1.6 mr in Zoom mode) does not place overly challenging requirements on the star trackers of structural alignment of the spacecraft. Since CIRAS is a technology demonstration, we plan to place the instrument in a variety of acquisition configurations including Global, Zoom, Pushbroom Zoom, Imagery and Winds modes. Some of these require changing the attitude of the spacecraft to support the acquisition.

3. DATA ACQUISITION MODES

The CIRAS uses a 2D focal plane that oversamples both spatially and spectrally. And with the system operating at 30 Hz, multiple frames are averaged to make a full dwell time (time it takes to make a resolution element in the scanning or pushbroom direction). The native sampling of the CIRAS FPA is 0.32 km per pixel and operating at a maximum rate of 30 Hz, one frame moves along track 0.23 km in pushbroom mode. Despite the good sampling, the resolution is limited by the slit (2 pixels) and signal to noise limitations.

Figure 3 shows a set of typical acquisition modes that can test the ultimate limits of the CIRAS. Although we identify 5 modes below, it is quite possible this list will change or modes deleted depending on time and funding limitations.

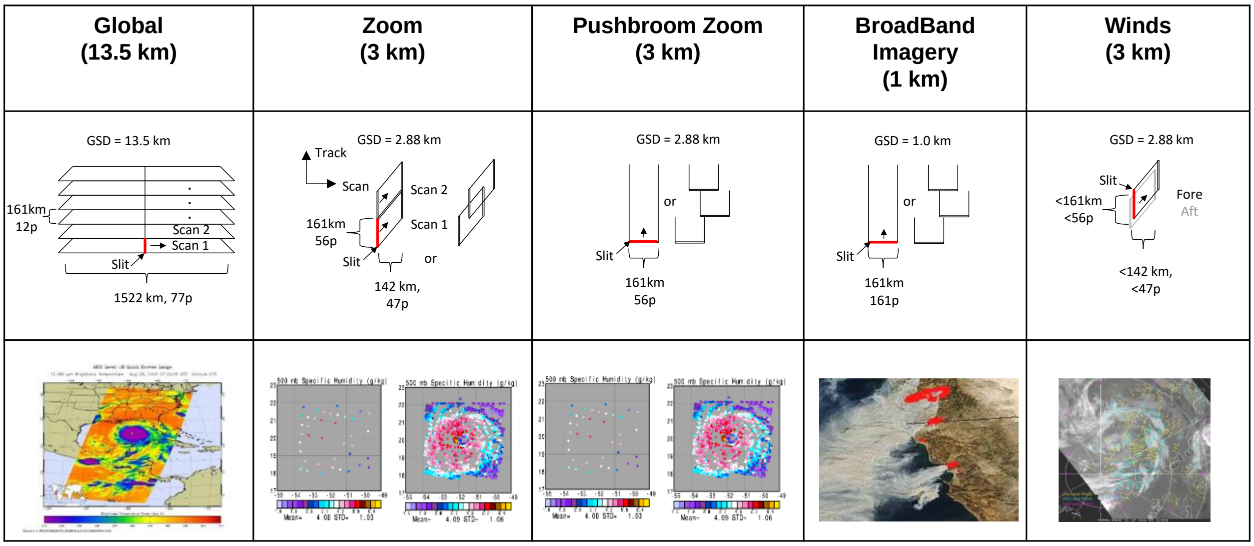

Figure 3. CIRAS can test multiple data acquisition modes. Here are a few examples. Orientation of slit shown in red for first scan in each case.

3.1 Global Mode

This mode achieves 13.5 km spatial resolution with global daily coverage and mimics the operational sounders currently flying. In this mode, the spacecraft is flying with the 1U x 2U side along the velocity vector and 1U x 3U side facing at nadir. The telescope projects the image of the slit onto the ground oriented lengthwise along track. As shown in Figure 3, the slit rotates with scan, but maintains good coverage. Binning occurs in the spatial direction (along track) and frame averaging occurs cross-track with the scan motion to make a full 13.5 km pixel.

3.2 Zoom Mode and Pushbroom Zoom Mode

Zoom mode achieves a smaller FOV over a smaller region to provide more soundings per unit area in these regions. It is achieved by slowing the scan rate in the Earth View and averaging a different number of pixels and Frames. The scan is slow and long, with each 2.88 km FOV covered in 0.433 s. With the satellite moving at 6.9 km/s, the pixel is blurred along-track by 2.99 km. This produces a trapezoidal spatial response. A second zoom mode, called "pushbroom zoom" has no scan blur in the spatial direction and a more square response. In this mode the satellite is nadir Earth pointing and rotated in the yaw direction by 90 degrees with the scan mirror pointed at nadir orienting the slit perpendicular to the track direction.

3.3 Broadband Imagery Mode

Recovering the NEdT lost by improving the spatial resolution is possible at the expense of spectral resolution. This can be achieved by binning in the spectral direction of the focal plan as well as spatial. The process of binning reduces spectral resolution and consequently vertical resolution, but may be sufficient for land thermal imaging including fire detection.

3.4 Winds Mode

Atmospheric Motion Vector (AMV) winds mode is possible by tracking water vapor features in two successive images obtained over the same space on the ground separated in time. This has been successfully demonstrated in GOES and MODIS Imagery. Since CIRAS measures the 3D profile of water vapor, it is expected that two successive images by a CIRAS sounder could produce 3D AMV winds. At 3 km spatial resolution, wind speeds would have to be in excess of 200 km/hr to be detected, but an experiment using CIRAS can help identify error sources in the AMV process. In winds mode, the satellite points forward 30°, acquires data for 51.2 s, points nadir, acquires data for 51.2 s, then backwards 30° for the same time, acquiring 3 successive images of the same region on the ground. This technique can be used in either of the zoom modes.

3.5 Spectral / Spatial Mixing Correction

The CIRAS takes advantage of a large 2D focal plane to relax alignment requirements. In order to benefit from this feature, a signal processing algorithm is required to reformat the data. The grating spectrometer works by dispersing the energy in the cross-slit direction. Any rotation of the dispersion direction relative to a row of detectors will result in a spatial point on the slit mapping onto multiple rows. Uncorrected this could result in spatial-spectral mixing. We can correct for this by selecting the rows we average for each spatial element (FOV). For example, in zoom mode, we average 9 rows of detectors for each 3 km FOV. The correction requires these 9 rows to be different for each spectral position along the detector array.

4. CIRAS DESIGN AND DEVELOPMENT STATUS

The CIRAS has completed preliminary design and is approaching the Critical Design Review (CDR). At the time of this writing, all design trades are complete, subcontracts for the optics (Ball), IDCA (IRCameras) and Phase 1 of the spacecraft (BCT) are in place, and the detailed design is progressing. Detectors have been fabricated and long lead procurements have been initiated for the optical components, electronics, and cryocoolers.

Figure 4. Picture of co-author Dave Ting using HOTBIRD detectors developed for CIRAS

4.1 HOTBIRD Detectors

CIRAS will use a 512 x 640 element 24 µm pitch JPL High Operating Temperature Barrier Infrared Detector (HOT-BIRD). The HOTBIRD technology is based on III-V compounds and offers a breakthrough solution for the realization of lower dark current and improving uniformity and operability compared to II-VI material (MCT) at lower cost. Low 1/f noise and high temporal stability allows CIRAS to use a slow scan for better sensitivity and less frequent calibrations. Figure 4 shows a photo taken using the CIRAS HOTBIRD detectors. The image reflects the high operability and good sensitivity of the device. Over a dozen usable Sensor Chip Assemblies (SCAs), consisting of the detector hybridized to a Readout Integrated Circuit (ROIC), were successfully fabricated on the first lot demonstrating the producibility of the HOTBIRD detectors.

4.2 Integrated Dewar Cryocooler Assembly (IDCA)

The SCAs will be mounted in an evacuated dewar called the Integrated Dewar Cryocooler Assembly (IDCA). As mentioned above the IDCA provides not only the vacuum environment but includes the cryocooler for the detector and cold filters for blocking Ghosting and out-of-band light. Early in the design phase we recognized that the MGS will produce a small amount of Ghosting that can introduce spectral mixing of energy in the spectrometer. Cold filters were designed to mitigate the problem and essentially pass only energy for half the spectrum over the corresponding half of the focal plane. One cold filter passes 4.0-4.6 µm and rejects everything out of this band (from 1.5-4.0 µm and 4.6-6.5 µm), while the other filter passes the 4.6-5.2 µm and rejects similar to the other filter. These filters will be mounted in close proximity to the detector and operated at the same temperature as the detector.

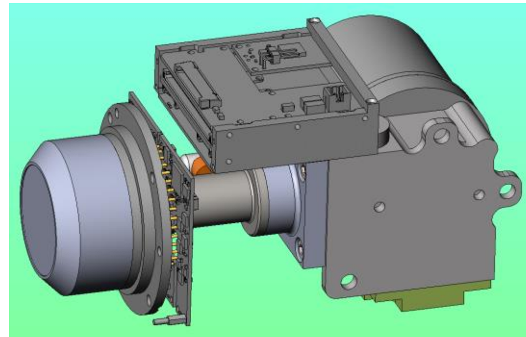

Figure 5. IDCA holds the detector in an evacuated dewar and provides cooling, spectral blocking, and readout of signals.

4.3 MWIR Grating Spectrometer (MGS)

The CIRAS MGS is a grating spectrometer based on designs developed by JPL and Ball Aerospace in the late 1990's and mid 2000's[9]. The CIRAS MGS consists of the camera, the collimator and the telescope, comprise the bulk of the CIRAS optical system as shown in Figure 6. The Spaceborne Infrared Atmospheric Sounder (SIRAS) and SIRAS-Geosynchronous Earth Orbit (SIRAS-G) demonstrated wide field all refractive grating spectrometer systems operating in the LWIR and MWIR respectively with spectral resolution and field of view comparable to the CIRAS. CIRAS is different in that it employs a silicon immersion grating developed by JPL. The immersion grating provides higher dispersion and allows more favorable reflective angles enabling a smaller spectrometer. Lens materials consist of Silicon, Germanium and IRG 25. The slit is similar to those developed by JPL for other spectrometer projects darkened with black silicon. The entire assembly is estimated to weigh less than 1.5 kg. Performance is excellent with near diffraction limited image quality, better than 50% transmission and less than 30 µm distortion at the FPA.

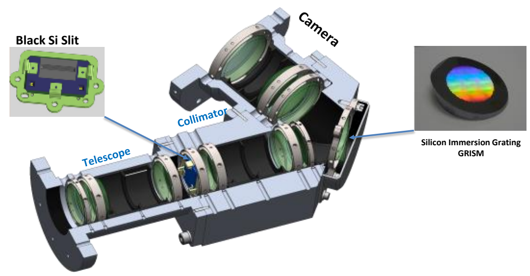

Figure 6. CIRAS MGS and telescope under development by Ball. CIRAS employs a silicon immersion grating and black silicon slit developed by JPL.

4.4 Mechanical Design

Packaging the required components into a 2U x 2U x 1U (20 cm x 20 cm x 10 cm) payload allocation turned out to be particularly challenging. Firstly the optical design requires two fold mirrors between the scanner and telescope in order to orient the beam. These fold mirrors protruded outside the volume in the original design. A redesign by Ball of the telescope and collimator reduced the overall length to just fit within the volume. JPL developed a mounting approach for the spectrometer that achieves a high degree of thermal isolation that fits within the package. At this time, all subsystems are be mounted to the spacecraft "top plate" which is a 2U x 3U plate of aluminum on the space side of the spacecraft. This makes integration and test of the payload and integration with the spacecraft easier.

In early designs, the spectrometer was attached to the IDCA so the spectrometer would maintain alignment with the focal plane as the structure distorts with temperature or other factors. While technically feasible, this approach turned out to be more costly than the project could afford due to the complexity of the design. Additionally the higher thermal load on the spectrometer from the hot IDCA exterior, even with isolation, turned out to be too great a load on the optics cryocooler. A simpler approach was adopted where the IDCA and spectrometer are independently mounted and aligned to each other using shims. The approach could ultimately lead to displacements of the spectrum during launch (from its position during ground calibration), as well as in orbit with thermal fluctuations. We plan to remove spectral errors during ground processing by recalibrating the spectrum to atmospheric absorption lines. We also can remove spatial misalignments by choosing the pixels we use to make a FOV during the binning process.

An unfortunate consequence of decoupling the spectrometer and the IDCA is an increase in the background emission from the dewar window since it now will be operating at around 305K. This increases the predicted NEdT (lower NEdT is better) for the system by a factor of 2 (was 0.1-0.25K now is 0.2-0.5K). The actual NEdT will depend on the ultimate temperature and emissivity we achieve for the window but even with the degraded NEdT we expect the system to perform well as a temperature and water vapor sounder. The better NEdT is on the longer wavelength side of the spectrometer in the water band. Future CubeSat sounders based on CIRAS can be designed with a more sophisticated dewar to enable a cold window (as done on AIRS).

4.5 Electronics Design

The CIRAS electronics consists of several independent boards providing unique functions for the payload. The Payload Control Electronics (PCE) provide power and communications with the CIRAS Scan Motor Control Electronics (MCE), the Motor Indexer Electronics (MIE) and the Housekeeping Electronics (HKE). The MCE board consists of a driver that controls the Lin Engineering 3709V stepper motor and with the PCE achieves the desired scan profile. Scan position is read out once per profile using an indexer consisting of an aperture attached to the motor shaft with hole identifying the home position through which an LED signal is sensed by a detector. The home position will be used to synchronize the data acquisition process by the spacecraft. The HKE reads temperature sensors from the payload and provides power conversion for the Detector Readout Electronics (DRE). Clocks and biases and A/D conversion for the SCA are provided in a small board next to the dewar called the Proximity Electronics. Digital data from the Proximity Electronics are multiplexed through the DRE which provides a Camera Link output that feeds directly into the spacecraft C&DH system. Cryocoolers are operated directly from the spacecraft bus.

4.6 Remaining Subsystems

The remaining subsystems for CIRAS include the Scan Mirror Assembly, Blackbody Assembly and the Optics Cryocooler (IDCA Cryocooler already mentioned above). The Scan Mirror Assembly (SMA) is in the design phase and consists of the mirror, the motor, the indexer and the mounts. The SMA and indexer is currently being designed, and the motor is undergoing testing. To date, we have been able to drive the motor with the desired scan profile using benchtop electronics. This testing allows us to adjust the phasing of the signals to the motor for best motion control and demonstrate the smoothness of the motion. The Blackbody Assembly will not have temperature control but will contain a precision temperature sensor. Mounting of the black silicon to the substrate and the mounting of the substrate to the payload are still in the design phase. The Optics cryocooler is one of 4 Ricor K508N cryocoolers the project is acquiring, only 2 of which will be used for flight. The Optics cryocooler will be attached to the optics assembly using a flexible heat strap.

5. SUMMARY AND CONCLUSIONS

The CIRAS is a technology demonstration of a hyperspectral infrared sounder operating in the MWIR. It is under development at JPL and scheduled for launch in the mid 2018-2019 timeframe. CIRAS incorporates new technologies including a wide field spectrometer employing an immersion grating, HOT-BIRD detectors, and a Black-Silicon blackbody. These new technologies combined with commercial technologies in camera and payload electronics, scanning, cryocooling and the spacecraft enable the CIRAS to be developed at low cost and in a CubeSat configuration. At this time, the detectors for CIRAS have been developed and procurements have been placed for the major subassemblies. We have demonstrated the scan profile motion required to achieve legacy imaging and the project is approaching the Critical Design Review (CDR). Compromises were made in the design to reduce cost including decoupling the IDCA and spectrometer that will ultimately degrade performance, but the approach is robust enough to still function as a high quality sounder and demonstrate the technology demonstration objectives of the mission. The CIRAS is expected to be completed in September of 2018 with a launch sometime in early 2019.

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